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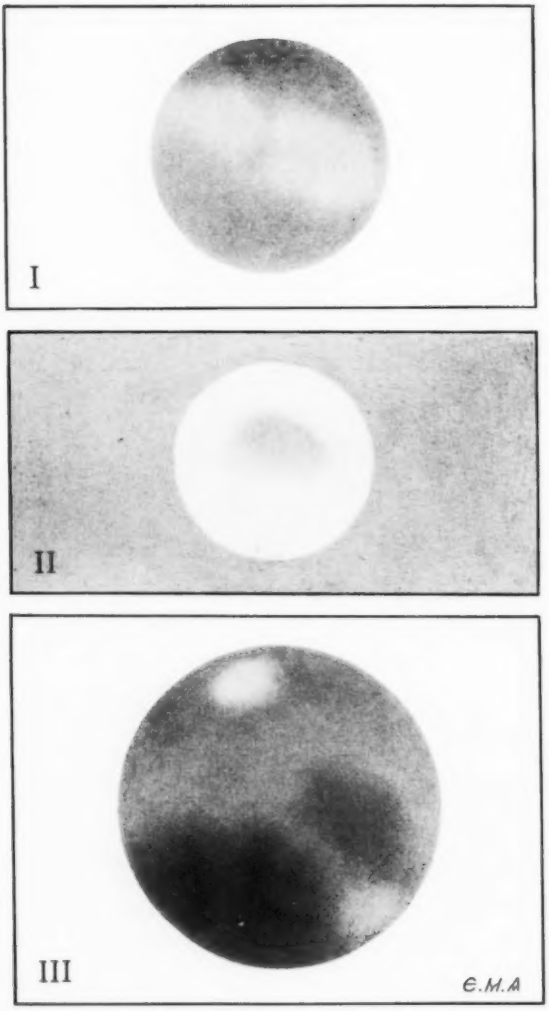
PLATE XI




THE FIRST THREE LARGE SATELLITES OF JUPITER IN TRANSIT

*Upper*—Satellite I, Antoniadi's observations, completed by details discovered by Barnard.

*Middle*—Satellite II, as seen by Antoniadi Sept. 28, 1927.

*Lower*—Satellite III, as seen by Antoniadi, with whitish southern spot seen by Barnard.

*Journal of the Royal Astronomical Society of Canada, 1939.*

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# ON THE MARKINGS OF THE SATELLITES OF JUPITER IN TRANSIT

By E. M. ANTONIADI

(with Plate XI)

IT was with varying success that several astronomers have tried to detect spots on these secondary planets, and such an enquiry was usually undertaken in all positions of those orbs around Jupiter. But as contrast enhances the brightness of their limb on the sky, thus fading, or quenching, marginal dusky markings, it is chiefly during transits across the primary that the configuration of these satellites can be best scrutinized with the aid of powerful appliances; and the appearances observed under these conditions form the object of the present paper.

## SATELLITE I.

Sometimes to Schæberle, Campbell, and Holden, using in 1891 the great Lick refractor, this moon projected on the sky did not appear spherical, but ellipsoidal, the longest axis seeming directed towards the centre of Jupiter. Such a shape could not, of course, be real: it was obviously due to the spots of the satellite, to the brightness of its equatorial regions and dusky north and south caps, deforming the circularity of the disk. The distortion is here analogous to that resulting from the markings of satellite III; or to that of the polar snows of Mars, seeming to protrude beyond the limb; or to the famous square-shouldered appearance of Saturn, due to the duski-

ness of the polar regions and to the occasional brightness of the temperate zones of that planet, according to the true explanation of Denning.

The colour of this moon appeared fiery yellow, and redder than that of satellite III to Holden, using the 36-inch Lick refractor, and to myself in the 33-inch of Meudon. Its yellowish, white, or even bluish appearance, with medium-sized appliances departs from reality, as large telescopes, with their powerful light-grasp, show colour much better than ordinary ones, and their evidence is decisive.[1]

As to the albedo, if that of Jupiter be estimated at 0.50, then that of satellite I could be rated at about 0.53. This moon is always seen like a bright little circle when projected on the dusky limb of the planet; it disappears farther inside the disk; and then gradually looks like a more or less greyish mass on the bright zones near the middle regions of Jupiter. Projected here on a very bright spot, it looks black; if transiting on a faintish belt, it may pass unnoticed; and if the belt be dark, then the satellite will appear as a bright circle on it. These facts are illustrated by the following observations. In 1760, Messier found this moon bright on or near the limb of Jupiter. Near the central regions of the planet, Bond saw the satellite dusky, or even black; Dawes as "an irregular grey spot, but never so dark by many shades as the third usually is"; Spitta, steel grey or almost black; Barnard darkish; Keeler pale greyish; Molesworth dull grey; the Rev. T. E. R. Phillips grey; Mr. Peek grey; myself generally grey. Cassini, in 1693, and Gale, in 1891, saw that this little globe was visible throughout a transit as a bright spot on the south equatorial belt of Jupiter.

Dawes found sometimes this body on the planet irregularly rounded, and, on one occasion, Burton drew it somewhat pointed to the north. In 1888, Holden discovered with the 36-inch Lick refractor that the satellite in transit showed two shades, one to the north, the other to the south, and that it also appeared as an elliptical

[1]Yet the high sensitiveness of the retina of some observers enabled them to accomplish feats in the detection of colour with moderate instruments. Thus Lockyer discovered the green areas of Mare Australe on Mars with a 6-inch refractor, while Eddie saw a brown N. bower to Mare Sirenum with only a 9¼-inch reflector,—a wonderful achievement indeed!

brightish mass, whose major axis, parallel to the equator of Jupiter, equalled 1½ times the minor axis. Two years later, Barnard, using the 12-inch Lick refractor and powers of 500 and 700, saw the satellite as two circular grey spots, of which the north one was larger than the south one. This most curious and unexpected appearance was confirmed by Burnham at the same time. It was due to the dusky caps observed by Holden, but reduced to two perfectly round spots by the much more prejudicial effect of diffraction in the minor Lick instrument. An appearance so delusive is exactly identical with that of the highly irregular little dusky spots, or oases, of Mars, which looked so perfectly and artificially circular to Lowell in his fine 18-inch refractor, so untowardly stopped down to the aperture of

Fig. 1.—Satellite I in transit, seen by Barnard as two unequal grey circles, with the 12-inch Lick refractor, and as a globe with grey polar caps in the 36-inch.

only 12 inches. "The circle," said the Flagstaff observer, "is the figure which encloses the maximum area for the minimum average distance from its centre to any point situated within it"; and thus Lowell was led to expatiate on the "strangely economic character of the oases in the matter of form." But the genius of Maunder opposed here to the American astronomer the fact, that "the circle is economic not only in the construction of irrigation works, but also in vision," the angle subtended by these minute planetary details being far too small to enable the eye to define the irregularity of their form; and this deceitful view of the satellite, as two unequal grey circles, constitutes an added confutation of the reality of these geometrical patterns[2] which are so plentiful on the Martian drawings of Schiaparelli and Lowell.

[2]This happy expression is due to the late Mr. A. Stanley Williams, a very great planetary observer and a worthy rival of Dawes.

In 1891, Barnard saw with the 36-inch satellite I in transit as an irregularly oval brightish spot, which was elongated almost from the south-west to north-east, and which was doublish, the smaller segment being to the west; and, in 1893, he distinctly saw with the large telescope that the satellite, again in transit, was round, but that it had a dusky north cap, and another south cap, both these being separated by a brightish belt, roughly parallel to the equator of Jupiter. This bright middle area was also seen by Molesworth in 1898; and, in 1928, the Rev. T. E. R. Phillips detected the polar caps as two parallel dark streaks. At Meudon I confirmed almost all these various appearances in 1926 and 1927; and, judging from the observations of Barnard in 1890 and 1891, I think that the north dusky cap is slightly larger than the south one, and that it extends farther north to west than to east. Such results demonstrate in a striking manner the overwhelming superiority of large telescopes over middle-sized ones in the definition of planetary detail.

With a 4½-inch refractor, Barnard saw this body brownish on Jupiter. It looked faint brown to Kempthorne, with an 8½-inch reflector, reddish brown to Townshend, using a 9½-inch mirror.

On one occasion, Holden found the shadow of this satellite brown in the 36-inch,—an appearance later confirmed by Perrine. The secondary spectrum of the great glass probably explains this brown tinge, especially if, as in the last case, the shadow was cast on a ruddy belt.

### Satellite II.

Once, in 1888, Schæberle noted with the 36-inch that this moon also appeared elongated in transit, and in the ratio of 1¼ to 1. This is again an optical phenomenon, due to a dusky spot, invisible at the time.

This satellite appeared to me bright yellow on the sky in the 33-inch.

The albedo of the orb in question seems to be the highest in the solar system after that of the particles composing the ring of Saturn, and may be estimated at about 0.60. This brightness is indeed so great, that it gives rise, by diffraction, irradiation, and poor images, to illusive appearances. M. Quénisset saw and drew in 1914, satellite II partly occulted by IV and looking much larger than the latter,

although the diameter of II is scarcely equal to 1,950 miles, while that of IV reaches 3,220 miles. Unlike satellites I, III and IV, II was never seen dark on Jupiter.

No one ever noted a marking on this globe. But, on 1927, September 28, I discovered on it, and held steadily in fine seeing, a striking and extensive dusky spot, situated somewhat above the centre of the tiny disk, and which was darker along its southern border.

The shadow of satellite II did not appear black, but greyish, to Buffham, Birt, Grover, Flammarion, Terby, Capt. Noble, Denning, Guillaume, Holden, and others. Also, it looked occasionally brown to Capt. Noble, to Knobel, and to Denning; and these impressions have been doubtfully attributed to a possible refraction of the solar rays in an atmosphere of the satellite, thus producing an effect like the coppery colour of our eclipsed moon. With regard to the observed faintness, we must not forget that this shadow is the smallest of the four, and that, consequently, it is comparatively more affected by diffraction than the others. In the 33-inch, it always appeared to me, like the others, blackish, not black, owing to the secondary spectrum.

### Satellite III.

The occasional elongated appearance of this moon on the sky must have been noticed by Herschel in 1797, when he suggested that the satellites of Jupiter might not be spherical. On one occasion, in 1850, Lassell saw this orb certainly not round,—an appearance confirmed by Secchi, Burton, and many others since. The mystery was admirably solved by the Rev. T. E. R. Phillips, who showed that the distortion was simply due to the spots of the satellite, and not to a really flattened figure.

Holden, Keeler, and myself found the colour of this satellite a strong yellow on the sky.

This ponderous globe, like satellites I and II, appears bright when internally tangent to the limb of Jupiter, and vanishes when projected farther inside the disk, in order to look dusky, dark, or even blackish, on the central regions of the primary. Such phenomena were first observed by the great Cassini, in 1665; and the marginal decrease in brightness of Jupiter generally accounts for them, although infinite complexity is introduced here by the duskiness of the

polar regions, the belts, the zones, the red spot, the south tropical disturbance, and the whitish or dark markings of the planet, as well as by the strongly uneven luminosity of the satellite itself.

On 1849, February 11, the eagle-eyed Dawes, using only a 6 1-3-inch refractor, discovered two roughly oval dusky spots on this moon in transit, which were situated chiefly in its northern hemisphere, and which appeared separated by a faint half-tone, stretching from south-west to north-east. This is indeed a wonderful achievement with such an aperture, and stamps this Englishman as one of the very greatest observers of all time. Dawes again drew these markings, in transit, on 1860, January 31; and on 1867, August 21, he curiously found them removed to the south-west when the satellite was once more in transit.

I was enabled to confirm in 1926 and 1927, at Meudon, the existence of all these spots: the dusky mark to north-west was larger and darker to me than the one to the east, and both showed a striking brown colour. The north-west spot was seen in 1850 by Lassell, in 1867 by Barneby, in 1884 by Davidson, in 1898 by Essam, in 1909 and 1911 by Innes, in 1910 by Phillips, and in 1927 by Rougier. The east spot was seen separately by Innes in 1909 and 1911. And both spots were observed as a single marking by Burr in 1867, by Burton in 1870, by Denning in 1886, by Mee in 1891, by Cammell in 1892, by Barnard in 1893, by Molesworth in 1898 and 1903, by Thomson in 1907, by Bougon in 1920, and by Steavenson in 1932. Lastly, the brown tint was seen by Lassell, Barneby, Burr, Denning, Cammell, Essam, and Bougon.

A whitish area, discovered by Innes in 1911 on the north-east limb of the satellite, was confirmed by me and M. Lyot in 1927. And, during the transit of 1894, September 23, Barnard found the satellite quite black, but showing a small oval brightish spot near its south-south-west limb. This mark has been included in my drawing, III of Plate XI, although I never saw it myself.

The results of Dawes would seem to suggest a very marked inclination of the axis of rotation to the perpendicular to the plane of the orbit. But the comparison of the heliocentric longitudes of Jupiter during his observations and mine does not countenance such an assumption.

The shadow of this moon was seen brownish by Swift.

## Satellite IV.

Colour estimations of this globe, the largest of all the secondary planets of the solar system, as shown by Mr. Stewart, are more contradictory than for the other moons of Jupiter. Thus Herschel found it, on the sky, ruddy, orange, dingy, and even bluish; Mædler and Engelmann bluish; Dawes and Webb ruddy; Perkins slaty and greenish; Espin pale blue; Spitta bluish; Holden pale lemon; Keeler pale yellowish white; Wilson purple and bluish; Waugh dull brown; Davis red; Molesworth strong bluish; once purplish; MM. Baldet and Lyot ruddy; the Rev. T. E. R. Phillips dull yellow; and myself dull yellow and often ruddy. The prevailing colour must be ruddy yellow, as shown by the evidence of the largest telescopes, and this is rendered certain by the fact that this satellite was seen brown in transit.

The albedo is here very low, probably inferior to that of Mars, say at about 0.16, but superior to that of the Moon and Mercury.

Cassini, in 1665 and 1677, first saw this satellite in transit "as black as a shadow" on Jupiter. The impression of Maraldi in 1707 and 1713, and of J. Pound in 1719 was a similar one. Since then, these black transits struck Prince, Hough, Burr, Dawes, Lassell, Webb, Key, Burckhalter, Pratt, Coleman, Baxendell, Spitta, Perkins, Miller, Denning, Hill, Barnard, Molesworth, M. Lyot, the Rev. T. E. R. Phillips, Mr. Peek, and myself. On 1926, August 17, satellite IV, although projected on the south equatorial belt of Jupiter, appeared to me in the 33-inch quite circular and absolutely as blackish as its larger shadow. It was at first mistaken for the shadow of another moon; and I say blackish, not black, because both the satellite and its shadow were naturally invaded by the extraneous light of the secondary spectrum.

Lassell justly wrote after the transit of 1859, December 7: "It was difficult to conceive that any object so dark . . . could ever appear as a bright one."

Yet this blackness is not constant. The satellite may appear very dark grey, dusky, faint, or even remain invisible in transit. Thus Lassell, Capt. Noble, Johnston, Isaac Roberts, and Smart saw it simply very dark, Macdonnell and Bougon dark, Webb "very pale" on 1835, January 26; and, during the transit of 1889, September 12,

such observers as Denning, Stanley Williams, and G. T. Davis could find no vestige of the satellite IV, projected on a belt of the northern hemisphere of Jupiter. A most interesting observation indeed!

Davis, Perkins, Miller, and Molesworth saw this moon dusky near the limb of the planet; Spitta, Baxendell, Perkins, and Macdonnell lost sight of it nearer to the limb; Spitta and Gledhill, on the other hand, found it black until egress on 1885, April 18; while Barnard, on 1890, August 13, and M. Lyot, on 1921, May 25, saw it at egress, when bisected by the limb of Jupiter, blackish on the planet and brightish on the sky. The albedo of this satellite must be inferior to that of the limb of the primary.

Lassell, Dawes, Burton, and G. W. Roberts, noticed occasionally

Fig. 2.—Satellite IV seen by Antoniadi as a circular black disc on Jupiter.

a lack of circularity of this moon, which may be accounted for by brighter marginal regions, encroaching upon the apparently black disk.

Satellite IV was seen brown in transit. Already in 1835, Webb thus called attention to its "rather ruddy" hue. Fifty years later, Smart found it dark brown, Leigh and Spitta of a chocolate colour; and, in 1890, Barnard, with the 12-inch Lick refractor, remarked on it a brownish tinge, or reddish black colour, which changed into black later.

## Generalities

*Phenomena Presented by the Shadows.*—Towards quadrature, the shadows of these satellites are seen elongated in a direction parallel to the equator of Jupiter. The largeness of the shadow of satellite

IV had been remarked already by Cassini in the seventeenth century, and was confirmed by Lassell and many others. Proctor and Buffham rightly explained it by a considerable penumbra. Large telescopes have revealed the penumbra of the shadows of the other three satellites. Trouvelot and Lumsden saw double the shadow of satellite I, Guillaume that of II; and I noticed that this deceitful phenomenon is due to the irregular refraction of rippling air.

*Rotation Periods.*—W. H. Pickering asserted that satellite I rotated in a period different from that of its revolution, and Barnard considered this probable. The same erroneous idea was expressed by Secchi, Proctor, Schæberle, and Campbell, for satellite III, to which Molesworth even assigned a period of $22^h\ 59^m\ 10^s.65$, believing that satellite IV also had a rapid rotation, of some $20^h$. But Herschel had rightly considered that all the four satellites presented, like our moon, always the same face to their primary,—a fact confirmed photometrically by Guthnick and Stebbins.

Visually, I found that satellites I and III in transit presented always the same markings, so that their period of rotation is manifestly equal to that of their revolution; and the same conclusion had been reached most ingeniously by the Rev. T. E. R. Phillips for satellite III, by its periodically deformed appearance, due to the spots of its surface.

Applying Sir George Darwin's inverse sixth-power law of the distance for the tidal drag exerted by Jupiter on the rotation of his four large satellites, I find the following results:

| Satellite | Approximate power of the brake on the rotation |
|---|---|
| I | 4,000,000 times more powerful than on Iapetus |
| II | 250,000 times more powerful than on Iapetus |
| III | 15,000 times more powerful than on Iapetus |
| IV | 500 times more powerful than on Iapetus |

Here I have applied M. Grenat's square of the density of the primaries. And as Iapetus, the 8th satellite of Saturn, has a rotation period equal to his revolution, the same is thus shown to be true for all the four large satellites of Jupiter.

*Physical Condition of these Moons.*—Mr. Stebbins found a decided diminution of brightness with phase for all these four satellites, and concluded that they have rough surfaces, like the Moon, such an

asperity being particularly marked in the case of satellite IV. Professor Henry Norris Russell thinks that satellites I and II are probably masses of rock. According to Mr. V. M. Slipher, the atmospheric band, so conspicuous in the spectrum of Jupiter, is absent from that of satellite III. The velocity of escape on these bodies is almost comparable with that of the moon; but as solar radiation at the distance of Jupiter is 27 times feebler than on Earth, the velocity of the gaseous molecules is there very considerably slackened, so that these satellites may have retained a highly rarefied atmosphere of heavy gases.

* * *

*Brown Markings on the Satellites of Jupiter and on the Largest Satellite of Saturn.*—We have seen that satellites I and IV were observed brown on the planet, and that the spots of satellite III in transit are also unquestionably brown. Now, Titan, ruddy on the sky, appeared brown in transit to Arthur Mee in 1892. We thus see that the largest satellites of the solar system show a tendency to have brown markings, whose nature is obviously totally different from that of the grey Maria of the Moon.

* * *

In concluding this enquiry, I cannot refrain from doing justice to the patience, zeal, and enthusiasm of the British amateur astronomers, who, although using only modest appliances, have yet so powerfully contributed to create and develop our knowledge of the intricate appearances presented by the tiny disks of these satellites. Nor can I forget to mention my profound indebtedness to my past director and master, Dr. Deslandres, the great French astronomer, for having allowed me, for so many years, the use of the most powerful refractor in Europe.

16 Rue Saussier Leroy,
Paris, 17$^{e}$, France.

# COLOURS ON JUPITER

By Walter H. Haas

IT has long been known that the belts of Jupiter are coloured, and until recently the reddishness they often exhibit was ascribed to the planet's supposedly semi-molten condition. But actual measurements have shown that the temperature is very low, and at present no satisfactory explanation of the colours exists. As far as I know, no one has ever carried on a systematic programme of observations of colours on Jupiter. I have done so visually and shall here indicate my results.

The primary difficulty with Jovian colour observations is the absence of any area of standard colour. The belts and zones are subject to variations in hue; even the polar shadings may alter. In 1938 I tried to use a colour-scale devised by W. H. Pickering for stellar and planetary work,[1] but it was found that the hues were not the simple spectral tints of the scale. To describe the hues exactly or even consistently is often difficult. In order to minimize errors, one ought to observe certain precautions. The entire programme should be carried on with one telescope and with a constant magnification. Work should be done only in a clear and dark sky, for haze and sky-background influence colour. If colour filters are used, the same ones should be used each time. Finally, observations must be frequent, not scattered, if they are to be of much significance; for not only do we want as nearly a continuous a record as possible, but we want to cover each section of the planet. Hues may differ in the same belt or zone at different longitudes on Jupiter.

The data available for study are the following:

(1) My own observations, amounting to 118 in 1936,[2] 308 in 1937, and 414 in 1938.

(2) 255 observations in 1938 by Hugh Johnson.[3]

[1] "The Colors of the Stars and Planets", W. H. Pickering, P.A., **25**, 419, 1917.

[2] "Jupiter in 1936", W. H. Haas, P.A., **45**, 195, 1937.

[3] "Jupiter in 1938", Hugh M. Johnson, P.A., **47**, 165, 1939.

(3) Scattered (one to seventy-five) observations and communications in 1936-8 by Ed Martz,[4] Hugh Johnson, Latimer J. Wilson, and others.

We now describe the colours and their changes region by region. The polar shadings were perhaps gray in 1936 and were somewhat purplish in 1937. In 1938 the south polar region was greenish gray and the north polar region bluish or purplish gray. The south south temperate belt was usually gray; occasionally bluish or reddish tinges were remarked. The same was true of the north north temperate belt. The temperate zones were an ordinary yellow-white in 1937 and 1938; but parts were duller than other parts, and the north temperate zone gradually became so dull it merged with the north polar shading in August-November, 1938. The north temperate belt was gray in April-July, 1936; much of it was then coppery for a month. It was rather bluish in April-June, 1937, and it was much redder in July-October of that year. It was bluish again in April, 1938, but was reddish from mid-May to early September. The south temperate belt was some tone of copper-red during all three years. The tropical zones were perhaps an ordinary yellow-white in 1936. The next year the south tropical zone was consistently white, but the north tropical one may sometimes have exhibited tinges of brighter colours. In 1938 the southern zone was white, perhaps becoming duller after August first, and the dark matter of the south tropical disturbance in it was somewhat bluish; the northern one was white, though perhaps rather tawny near June first, and may have become brighter after August first. The south equatorial belt was bluish gray in 1936; one section was reddish in July. It was gray tinged by blue in April-May, 1937, was sensibly gray in June-August, and was reddish in September-October. It was reddish or tannish all through 1938. The north equatorial belt was some tone of coppery red all three years, but the hue varied much in its exact shade. For example, the belt was probably redder in the autumn of 1937 than in the summer. The equatorial zone was lemon yellow in the autumn of

[4] "Activity in Northern Hemisphere of Jupiter", Ed. Martz, A.A., **2**, 69, 1936.

1937, the exact tint varying. In 1938 it was the dullest zone on the planet, looking dull yellow or tawny-coloured.

Not only do the colours change gradually, as discussed above; but they also often vary in short periods, noticeable changes occurring rapidly and apparently irregularly at intervals of only a few days. One must be cautious in investigating these rapid changes, for errors in observation produce exactly the same results. The rapid changes affect most the low-latitude belts and zones, just those portions of the planet that direct observations of detail show to be most active. Observation of the relative intensities of the belts in 1938 gives indirect support to rapid changes of colour by showing that analogous rapid changes in intensity do occur. For example, the section of the south temperate belt near 75° (II) was lighter than the north equatorial, south equatorial, or north temperate belt in that part of the planet on July 11; it had become darker than any of them by July 15. The section near 310° (II) darkened in this same manner between July 16 and 19.

A by-product of the observations was independent evidence about a condition known to students of colour, differences in the colour-sensitivity of different eyes; i.e., some eyes are unusually sensitive to long (red) wave-lengths and others, to short (blue) wave-lengths. Johnson saw blues and greens where I could discern only grays, and I saw reds where Johnson found browns or grays. The evidence, though rather meagre, is not limited to these two observers. It is possible that differences in colour-sensitivity of eyes are of considerable significance in explaining differences in the planetary drawings of different observers; but this subject is a separate problem, demanding much investigation and lying outside the scope of this paper.

Certainly the best way to investigate these Jovian colours would be by means of monochromatic photography. We should take in rapid succession photographs with several different colour filters. The process could be repeated at two-hour intervals, as rotation brought new portions of the planet into view. The true colour could then be determined by a study of the different images, for the intensity of a coloured region would be different on photographs taken with different colours. Some work of this sort has already been

done, e.g., at Mount Wilson more than two decades ago by R. W. Wood;[5] but to the best of my knowledge, no results based on an extensive programme have yet been published.

Since all lines of evidence indicate that the visible surface of Jupiter is gaseous, there can be little doubt that we somehow have to deal with selective absorption by gases. However, we have not at all explained how the mechanism acts. Any theory of the colours must explain their variations. The hues on Jupiter remain one of the unexplained mysteries of planetology.

New Waterford,
Ohio, U.S.A.

[5] "Monochromatic Photography of Planets", R. W. Wood, Ap. J., **43**, 310, 1916.

# STELLAR ENERGY*

By Henry Norris Russell

THIS lecture should begin by an apology to the audience. The speaker to-night should be the man whose recent and brilliant work has inaugurated a new and very promising stage of astrophysical study—Professor H. A. Bethe of Cornell. The planners of the programme can plead but one excuse—his results had not been announced when it was prepared.

They are not yet published in detail; but Professor Bethe has most generously given me a full copy of the proof of his forthcoming paper,[1] and amplified this in personal conversation. What there is of novelty in the present discussion should be credited entirely to him, and not to myself. Indeed my report, apart from this, is mainly upon the work of others in a field in which I did a little pioneering a good many years ago.

A century of precise measurement has furnished astronomers with a large accumulated capital of facts about the stars. One of the most remarkable things that is thus revealed is that the stars differ greatly among themselves in some properties, and relatively little in others. For example, the luminosity—the rate of radiation of energy—ranges (roughly) from a million times the Sun's luminosity to a thousandth part of it, a ratio of a billion to one. The diameters run from at least 1,000 times the Sun's down to 1/30 or less, a range of thirty-thousand-fold. For the masses, the range is roughly from 100 times the Sun to 1/10 of the Sun, a thousand-fold. But surface temperatures more than ten times the Sun's or less than 1/4 that of the Sun are practically unheard-of, so that the known range is only forty-fold.

Why should such enormous diversities exist? The limitation of our study is set, on one side, by the obvious fact that we cannot see a star unless it shines—that is, unless it gives out enough light to be perceptible at stellar distances. This obviously sets a limit to our knowledge of *faint* stars, and of *small* stars—which, other things being equal, will shine less brightly because they have fewer square

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*Reprinted from the Proceedings of the American Philosophical Society, vol. 81, no. 2, p. 295. This 200-page number contains a series of eleven important astronomical papers given at a Symposium on Progress in Astrophysics. The price of the book is $1.00, paper bound.

[1] *Phys. Rev. 55,* 434, 1939.

miles of surface, and still more to the study of *cool* stars (of low surface temperature). The heat radiation per square mile varies as the fourth power of the temperature, and a forty-fold increase in the latter changes the former by a factor of about two and a half million. Moreover, at low temperatures, most of the radiated energy is in long infra-red waves, invisible to the eye, so that a star—like a mass of hot iron—ceases to be visible in the dark, long before it stops giving out heat.

But there is no such limitation on the side of great brightness. If we fail to find still brighter stars—though we are fishing for these in very wide waters—it must be because there are no such fish in our sea. Nature herself must in some way set a limit to the brightness attainable by a star—at least as a permanent affair, for we know that the short-lived outbursts of supernovæ are enormously more intense. Such a limitation would explain why stars of very large diameter are never found to be very hot—if they were, they would give out too much light; but it has no obvious relation to the mass of a star.

A notable advance was made more than twenty years ago when it was found observationally (first by Halm) that there is a close relation between the mass of a star and its luminosity. All later work has confirmed this, and it now appears that, over almost if not quite the whole available range, the total heat-radiation of a star is nearly proportional to the fourth power of its mass. The most remarkable feature is that, for a given mass, the luminosity does not depend much upon the size of the star—the large ones are cool, and give out less heat per square mile, the small ones hot, and give out more; but the net product is nearly the same.

Eddington's explanation of this, completed fifteen years ago, marks the first, and, even now, the greatest success of modern atomic physics in interpreting the stars.

Since the work of Lane in 1870, it has been realized that, if the familiar laws of perfect gases could be applied to the interior of the Sun, the central temperature must be many millions of degrees. The result may be written

$$T = 11.5 \frac{M}{R} \frac{Y}{X} \mu,$$

where $T$ is the temperature in millions of degrees, $M$ the star's mass

and $R$ its radius, $\mu$ the mean molecular weight of the material, and $Y$ and $X$ quantities depending on the "density-model," that is, the law in accordance with which the density increases toward the centre.

Calculations for different laws of density-distribution show that the "model" has a rather small influence. If the density were everywhere the same, $X$ and $Y$ would be 1 at the star's centre. On the model to which Eddington's calculations led, the central density was 54 times the average ($X = 54$); but $Y = 92$, so that the central temperature for the Sun comes out 19,700,000°. A model recently calculated by Chandrasekhar makes $X = 88$, $Y = 171$, and the temperature 22,300,000°; still another, reported by Bethe, 20,300,000°—all provided that $\mu = 1$. There are good reasons to believe that these "models" give a fairly correct idea of the situation, and therefore that the central temperature of the Sun is close to twenty million degrees—provided that the molecular weight is 1.

But, under ordinary circumstances, $\mu$ is 1 for hydrogen, 4 for helium, 16 for oxygen, 56 for iron, and so on, so that the calculated internal temperature of the Sun would depend enormously on its assumed chemical composition.

Fortunately for us theorists, the situation is simpler inside the stars; for the outsides of the atoms—the electrons which surround the nucleus—are pretty well knocked off. A hydrogen atom (with one electron) is broken into 2 particles, a helium atom into 3, one of oxygen into 9, and one of iron into 27 (or perhaps 25, if the two tightest bound electrons stay with the nucleus).

The average mass of a free particle (which is what counts) then comes out 1/2 for hydrogen, 4/3 for helium and nearly 2 for all heavier atoms. So we can conclude that the central temperature of the Sun is close to 10 million degrees if it is pure hydrogen, 27 million if it is all helium, and 40 million if it is all composed of heavy atoms—and the result for any assumed mixture can easily be computed.

The temperature of the Sun's surface is but a few thousand degrees. Heat will flow outward from the hot interior "down grade" and the surface will adjust its temperature so that it loses by radiation into space just the amount which it gains by transmission from the deep interior. The rate of this transmission thus determines how bright and hot the Sun (or any other star) will be; it takes place

mainly by the transfer of radiation from atom to atom through the gas; and the net opacity, which determines the rate of transfer, may be calculated with considerable accuracy, on principles developed by Kramers.

When the net flow of heat out to a star's surface is thus calculated, it is found that it depends relatively little on the "model," and not much upon the radius, but changes rapidly with the mass—at very nearly the rate indicated by observation.[2]

The mass-luminosity relation is thus explained—and with it the fact that stars of mass less than one-tenth the Sun's have not so far been detected—they are presumably too faint to be seen; and our failure to discover very large masses is connected with the absence of stars of very great luminosity.

Eddington's theory, however, predicts that the luminosity of a star, other things being equal, should change very rapidly with the mean molecular weight of its material (about as its seventh power). A star composed almost entirely of heavy atoms (with $\mu = 2$) will be so hot inside that it will shine brightly, whereas one composed mostly of hydrogen will be cooler inside—and fainter outside by several hundred-fold (the exact amount involving refinements of calculation omitted here).

The observed luminosity of the Sun is about midway between these limits, and may be accounted for, according to Strömgren's calculations, if one third of the material, by weight, is hydrogen, and the rest heavy atoms; or with more hydrogen if helium is present; for example, 60 per cent. hydrogen, 36 per cent. helium, and 4 per cent. heavy atoms. The mean molecular weight comes out 0.98 and 0.67 in the two cases, and the central temperature 19 million and 13 million degrees.

Repeating his calculations for other stars for which we have reliable data, Strömgren finds very nearly the same composition for Sirius A—the bright star, not its faint companion—for Capella, and for several others. Some stars contain less hydrogen, *e.g.* $\zeta$ Herculis A, which is four times as bright as the Sun though of very nearly the

[2]Certain complications which arise in the more massive stars, where radiation-pressure becomes a sensible fraction of gas-pressure, are neglected in the above account, for brevity.

same temperature and mass. Its computed hydrogen content is 12 per cent. (if there is no helium).

The observed mass-luminosity relation is now completely accounted for on principles derived from general atomic theory—but a new phenomenon takes its place to be explained. Why should so many of the stars contain almost the same amount of hydrogen? This is obviously not the kind of question which can be answered by a general theory of the type already described; and there are other much more obvious properties of the stars of which this is also true. For example, if we plot the luminosities (or the stellar magnitudes) of the stars against the surface temperatures (or the spectral types) we obtain a now very familiar diagram which shows marked peculiarities. The greater portion of the dots representing the stars lie in a narrow strip—indicating the existence of a "main sequence," having at one end bright, white stars, of great luminosity, large mass, and high surface temperature; and at the other faint red stars, their opposites in all three respects. The Sun is a typical member of this sequence, about midway in it. Calculating the diameters, we find that the stars at the top of the sequence are larger and less dense than the Sun, those at the bottom smaller and denser; but these differences are not very great, and most of the enormous range in brightness from one end to the other arises from the differences in surface temperature. The central temperature varies still less—it is some 30 or 35 million degrees for the stars at the top of the list, and may be as low as 12 or 15 million for the faint red ones at the bottom.

Almost as conspicuous as the main sequence (and indeed more so in a list of naked eye stars, which automatically picks the bright ones) is a wider, but definite, band, beginning with stars of about the Sun's surface temperature (Class G) but some fifty times the Sun's brightness, and extending to some of the reddest known stars, which give off several thousand times as much heat (though not visible light) as the Sun.

These giant stars (so named for their brightness) deserve the name for their size. Capella, which is a little cooler than the Sun, and 120 times as luminous, must have about 16 times the Sun's diameter. At the other end of the giant sequence come huge objects several hundred times as big as the Sun. The masses—according to the rather scanty evidence which alone is available, after careful

searching—are about the same as for main-sequence stars of equal luminosity. For Capella alone is an accurate value known, 4.2 times the Sun's mass. This makes its density hardly more than 1/1000 that of the Sun, and its central temperature (if built on a similar model) less than 6 million degrees. For the great red star ζ Aurigæ, the mean density is one nine-millionth part of the Sun's, and the central temperature (for the same model) but 1,200,000 degrees.

At the top of the diagram are scattered points representing the super-giant stars, extremely luminous, and with all sorts of surface temperatures. They must be of large diameter, and low density and internal temperature. The region below the giants and to the right of the main sequence is almost vacant, as is also that below the main sequence to the left. It is in this last region that we should find points representing stars with internal temperatures higher than twenty or thirty million degrees—and there are hardly any[3]—except down at the bottom, the famous white dwarfs (like the companion of Sirius), somewhat less massive than the Sun, less than one per cent. as bright, and comparable in diameter with Uranus or Neptune. The mean densities of these bodies are as great as 100,000 times that of water, and they represent a "degenerate" state of matter, in which as many electrons are jammed into every cubic centimetre as the quantum-laws will permit. They are surprisingly well understood, but do not belong to our present problem.

The luminosity-spectrum diagram reveals one more important fact. There are a great many stars with central temperatures of 20 to 30 million degrees, a good many with lower central temperatures, and very few, if any, which are hotter inside, except perhaps the white dwarfs. Why should this be? This ties up with an older and more fundamental question:—Why do the stars keep on shining?

When first the Sun's heat was measured, it was realized at once that it could hardly be maintained, even for the duration of history, by ordinary chemical combinations—what we now describe as reactions between whole atoms. A far larger source of energy is found in a slow contraction, compressing the gas and turning the gravitational potential energy into heat, and this explanation, due to Helmholtz and Kelvin, was still accepted forty years ago. The energy-

[3]There are a few white stars about as bright as the Sun, for which we have not yet sufficient data to say anything definite.

supply thus available for the Sun's past history is about thirty million times its present annual expenditure (depending somewhat on the assumed model). But at least half this must still be stored inside the Sun in the form of heat, so that less than fifteen million years of sunshine can be accounted for.

But the Sun has been shining and warming the Earth, very much as now, throughout geological history, which is certainly a hundred times as long as this. There is only one place in the known universe to look for so vast a story of energy—and that is in the minute nuclei of atoms. From these nuclei is liberated the energy of radio-activity —which is of the required order of magnitude, though rather small. But radio-activity itself will not meet our needs, for it takes place at a rate uninfluenced by conditions external to the nucleus—such as the surrounding temperature. To account for the observed variation of luminosity with mass, we would have to assume that in some inscrutable way the amount of active material had been exactly proportional "in the beginning" to the mass of each star, so as to provide the proper heat supply to maintain its radiation; and also that practically none of it had been allowed to enter the Earth or the other planets—for otherwise their surfaces would be red-hot or even white-hot.

It is necessary, therefore, to assume that the great store of energy upon which the stars draw becomes available only under stellar conditions—that is, obviously, at temperatures of millions of degrees.

The whole course of nature teaches that it would not become available abruptly, but at a rate increasing with the temperature, and probably increasing very rapidly. But here appears a difficulty. If too much heat should at any time be liberated inside a star for the steady process of escape to the surface to carry off, would not the material grow hotter, "turn on" a still more rapid supply of heat, till some tremendous explosion ensued?

The answer lies in a curious property of a gravitating star. As we have already seen, it must grow hotter inside if it contracts; but the gravitational energy released by the contraction is more than enough to supply this heat, and leaves a balance available for radiation. Only as heat is lost into space can the temperature of the interior rise. If just enough heat is liberated from some sub-atomic process, there will be a steady state; if too little, contraction will

supply the rest; if too much, this contraction will be converted into an expansion. This expansion will lower the internal temperature, and shut off the over-supply. The Sun has an internal store of heat equal to at least eight million years' outgo. The sudden introduction into the interior of even a thousand years' heat supply would therefore produce very little effect (unless it were localized in a small region, where it might cause trouble).

One other thing was clearly understood, twenty years or so ago; the reactions which provide the stars with their energy must be accompanied by a perceptible loss of mass. The theory of general relativity indicated that mass and energy should be interconvertible, at the rate of $c^2$ units of energy (ergs) for one unit of mass (gram), where $c$ is the velocity of light. The Sun's rate of loss of energy by radiation ($3.8 \times 10^{33}$ ergs per second) is far too great to be comprehensible in ordinary terms; but, if measured in mass-units, it means that the Sun is actually losing 4,200,000 *tons* of energy every second! The Sun's mass ($2 \times 10^{33}$ g) is so great that even at this enormous rate, it would take 15 billion years to reduce it by one part in a thousand.

The nature of the process—or, at least, of one process—by which this transformation of mass into energy can take place, is now well understood, since it can be made to happen in the laboratory, in many different ways. This is the transformation of atoms of one sort into another, with the appearance of an amount of energy corresponding to the change in total mass; and it is to this that we now look as the source of stellar energy.

The alternative hypothesis, that positively and negatively charged particles (protons and electrons) may utterly annihilate one another, with the appearance of the whole amount of energy corresponding to the sum of their masses, has now been dropped, since no evidence of it has been observed. It does appear to happen for positive and negative electrons; and judgment may well be reserved about "heavy electrons" (mesotrons) till more is known about them.

The masses of the lighter atoms (including their outer electrons) are given in Table I. They can be very accurately determined—mainly with the mass-spectrograph. The various isotopes—atoms of different weight, but the same chemical properties—are of course listed individually.

TABLE I

MASSES OF LIGHT ATOMS[1]

| Name | Symbol | Charge | Mass |
|---|---|---|---|
| Electron | e | –1 | 0.00055 |
| Neutron | n | 0 | 1.00893 |
| Hydrogen | H | 1 | 1.00813 |
| Deuterium | $H^2$ | 1 | 2.01473 |
| Helium | $He^3$ | 2 | 3.01699 |
| " | $He^4$ | 2 | 4.00386 |
| Lithium | $Li^6$ | 3 | 6.01686 |
| " | $Li^7$ | 3 | 7.01818 |
| Beryllium | $Be^9$ | 4 | 9.01504 |
| Boron | $B^{10}$ | 5 | 10.01631 |
| " | $B^{11}$ | 5 | 11.01292 |
| Carbon | $C^{12}$ | 6 | 12.00398 |
| " | $C^{13}$ | 6 | 13.00761 |
| Nitrogen | $N^{14}$ | 7 | 14.00750 |
| " | $N^{15}$ | 7 | 15.00489 |
| Oxygen | $O^{16}$ | 8 | 16.00000 |

From the table it appears that if four hydrogen atoms could in any way be converted into one helium atom, a loss of mass of 0.02866 unit would result. This is 1/141 of the original mass. If, therefore, a thousandth part of the Sun's mass were hydrogen, and could be transmuted into helium, energy enough would be released to keep the Sun shining for 106 million years.

The excess of the tabulated mass above an even value evidently represents the possible value of the given atom as a source of energy. This excess is fairly considerable for most of the lighter atoms; but oxygen, carbon and helium are relatively very stable. Some atoms heavier than oxygen are still further "down"; but the differences are small and need not concern us here. Per unit of mass, hydrogen is much the best source of energy.

Two types of nuclear reaction, in the laboratory, give rise to reactions of the sort considered:—the penetration into a heavier nucleus of a neutron, or of a charged particle (proton, deuteron, or alpha-particle). The former are the easiest to produce artificially—since the other nucleus does not repel the neutron. They occur in great variety, and liberate large amounts of energy. For this very

[1]These values are from Bethe's computations, with some changes from his latest work.

reason, it appears that they are not of much astrophysical importance. They happen *too* easily. If there were a lot of neutrons in the interior of a star, they would all collide with atomic nuclei of one sort or another—sometimes building up a heavier atom, sometimes causing the emission of some other particle—and they would be used up in the process, in the twinkling of an eye. There might be an almost explosive outburst of heat (under the altogether unnatural conditions which we have imagined) but anyhow the neutrons would be gone, and similar reactions would occur in future only if "new" neutrons were produced by other nuclear reactions. A careful study by several investigators has shown that this should happen so very rarely that its effects can be neglected.

We are left, then, as a steady source of energy, with the penetration of one charged nucleus into another. The repulsion between the two is always so great that only an exceptionally violent head-on collision between particles moving much faster than the average would be effective. The probability of such a collision has been calculated. It diminishes very rapidly with the charges of the particles, so that a proton is vastly more likely to succeed than an alpha-particle, while, even so, it stands very little chance of getting into a nucleus with a larger charge than oxygen (provided, at least, that the temperature is not more than twenty million degrees).

What happens after the proton gets in depends on the individual peculiarities of the nucleus which it has hit. It may simply go in and stay—producing a new nucleus greater by 1 in both charge and mass; or a positive electron may be ejected, leaving a nucleus of the same charge as before but of greater mass; or the old nucleus may break up into two or more pieces—one of which is usually an alpha-particle. None of these changes can happen if the hypothetically resulting nucleus is heavier than the reacting particles, for a quite impossible amount of energy would have to be supplied from no known source. If the mass of the product is less than that of the two particles, the excess energy will appear as kinetic energy when the nucleus breaks up, or an electron is ejected;[4] in the first case, it appears as radiation—a gamma-ray.

All three processes occur in the stars.

The astrophysical importance of reactions of this type was first

[4]Much of the energy in this case is believed to be carried off by that elusive particle, a neutrino.

pointed out by Atkinson. They have been discussed by von Weizsäcker, Gamow and Bethe, and enough is now known about the properties of nuclei to give a pretty clear picture of what would happen.

First. The one stable thing in this microcosm of change is the alpha-particle ($He^4$). Apparently nothing can happen to it. The nuclei which might imaginably be formed by collision with a proton ($He^5$ or $Li^5$) are unstable, and do not exist at all; a collision of two alpha-particles would give $Be^8$, which is slightly unstable, and breaks up again. Three fast-moving alpha-particles, colliding simultaneously, might possibly form $C^{12}$ with liberation of energy; but such an event is so very improbable that it can be neglected, except at much higher temperatures.

If, then, hydrogen is "the fuel of the stars" helium is the ashes.

Second. The other light nuclei, up to and including boron, are highly susceptible to proton collisions. The different ones go through various transformations, but every sequence ends irrevocably in helium—for example, $Li^7 + H = 2\ He^4$, $B^{11} + H = 3\ He^4$. (In this last case the nucleus breaks into three pieces—all helium.) Hence these elements, if originally present in a star, would be successively exhausted as the reactions went on. If we imagine a mass equal to the Sun's slowly contracting from a large size, with increasing central temperature, then, according to Bethe, the reaction which eats up deuterium would happen fast enough to supply the star's radiation, when the central temperature was 360,000° (more or less, depending on the amount present).

So long as any considerable amount of deuterium remained, the star would not contract further. As it was exhausted a new contraction would begin, to be halted when the central temperature was about 2,000,000° and lithium began to be transformed and used up. Beryllium would have a similar fate at a central temperature of 3½ million degrees, and the two isotopes of boron at five and nine million. Since the Sun's central temperature is much higher than this, there can be practically none of any of those elements left in its interior. At the surface, spectroscopic evidence shows that all three are present, but in very small quantities.

Third. At a temperature somewhat above fifteen million degrees, carbon begins to be attacked, and something quite new happens, which is tabulated by Bethe as follows:

| | | | | | | |
|---|---|---|---|---|---|---|
| $C^{12}$ | + H | = $N^{13}$ | + $\gamma$ | 2,000,000 | years |
| | $N^{13}$ | = $C^{13}$ | + $\epsilon^+$ | 10 | minutes |
| $C^{13}$ | + H | = $N^{14}$ | + $\gamma$ | 50,000 | years |
| $N^{14}$ | + H | = $O^{15}$ | + $\gamma$ | 50,000,000 | years |
| | $O^{15}$ | = $N^{15}$ | + $\epsilon^+$ | 3 | minutes |
| $N^{15}$ | + H | = $C^{12}$ | + $He^4$ | 2,000 | years. |

The proton goes into $C^{12}$ and builds up $N^{13}$ (the spare energy escaping as a $\gamma$-ray). This is one of the artificial radio-active elements, which has been produced in the laboratory. It emits a positive electron ($\epsilon^+$) and goes over into the carbon isotope $C^{13}$. The next proton turns this into ordinary nitrogen $N^{14}$, and another produces a radio-active oxygen $O^{15}$ which goes over into "heavy" nitrogen $N^{15}$. A proton collision might build this up into ordinary oxygen $O^{16}$; but Bethe calculates that it is ten thousand times more probable that it would split the nucleus into two parts, one of which is helium, and the other the original carbon $C^{12}$, ready to be used over again! The carbon is not consumed, but acts as a catalyst for the transformation of hydrogen into helium, and we have a regenerative process, which should continue until all the hydrogen has been transformed.

Four of the six steps here described have already been observed in the laboratory. The other two (involving collisions of protons with nitrogen) can reasonably be inferred from known data. The average length of time during which an atom of each kind may be expected to last before its next adventure, is given in the table. The $N^{14}$ + H reaction is the slowest; it will then be the "bottle-neck" for the whole process. Bethe's calculations show that it would supply energy enough for the Sun at a temperature of 18,300,000° (assuming 35 per cent. of hydrogen and 10 per cent. of nitrogen). As the rate of reaction increases as the 18th power of the temperature, it would do the work, with 1 per cent. of nitrogen, at a temperature of 20,800,000°. Now these temperatures, which are calculated from pure nuclear theory, agree excellently with the central temperature of the Sun, as calculated from astrophysical data. An almost equally good agreement is found for Sirius (22 million from theory, 26 from observation), and for the very hot and massive star Y Cygni (30 and 32 million). Moreover, the gradual changes in light, diameter, density and surface temperature for stars of different mass along the whole main sequence are in excellent agreement with the results of the theory.

It appears, then, that one great part of the problem of the source

of stellar energy has been fully solved. The main sequence is explained in detail.

There are still worlds left to conquer. The very rapid energy-liberation in the giants cannot be accounted for in the same way. It might be assumed that they are built on the same sort of model as the main-sequence stars, but contain larger quantities of lithium, beryllium or boron—but this is a far-fetched idea, and does not explain why they form a sequence in which the reddest stars are the brightest. It is also possible, as Gamow, Öpik, and others have suggested, that they are built on quite a different model, with relatively small and dense cores, which may be as hot as those of the main-sequence stars or hotter. Much more is likely to be done on this problem within a few years.

Reactions involving heavier nuclei are possible, but they would occur at significant rates only at higher temperatures, and so would not have a chance to happen if there were any carbon in the stars—as there assuredly is. If, at the other extreme, we had a star composed originally of pure hydrogen, it might get energy by the following chain of reactions, also according to Bethe:

$$\begin{aligned} H + H &= H^2 + \epsilon^+ \\ H^2 + H &= He^3 \\ He^3 + He^4 &= Be^7 \\ Be^7 + \epsilon^- &= Li^7 \\ Li^7 + H &= 2\ He^4. \end{aligned}$$

Two protons form a deuteron—a slow reaction; the latter goes over almost at once into $He^3$; this with an alpha-particle forms a known isotope of beryllium, which turns to lithium and then to helium—the net result being, as usual, the building of four hydrogen atoms into one of helium.

The rate of this process changes much more slowly with the temperature than that of the carbon cycle. Bethe suggests that it may supply the energy in the coolest stars of the main sequence. Present data do not suffice for a decision.

Two large questions remain to be mentioned.

First, What will be the history of a star? The first portion, till the carbon-cycle is "turned on," has already been described. The star will then keep shining as a member of the main sequence, for a very long time—gradually using up its hydrogen, increasing the mean molecular weight, and growing brighter, hotter, and a little

larger. At last, when the hydrogen is exhausted, it must contract, become fainter as well as smaller, and end up, if of small mass, as a white dwarf. A large mass should contract to a still higher density —how far, no one can yet say. The Sun should have a good ten billion years to go before it begins to fail. Meanwhile as it grows more luminous, the Earth should gradually grow warmer—at the rate of about 1° Fahrenheit in 100 million years.

Finally, Where did the carbon, in the Sun—and also the oxygen and heavier atoms—come from? There is nothing in the reactions sketched above which can form them, and the careful studies of von Weizsäcker and Bethe have found no chance of the production of more than the merest traces by any side-reactions. Yet present evidence indicates that nearly two-thirds of the Sun is composed of such heavy atoms—for, if there were fewer of them, and more helium, the molecular weight would be less, and the internal temperature too low to start the carbon-chain running.

It seems necessary to assume that they are *older than the stars*—constituents of the primitive matter of which these were formed. Von Weizsäcker has suggested—in accordance with certain forms of the theory of the expanding universe—that, at some remote time, the matter in the universe, or a great part of it, was concentrated into a vastly smaller compass than at present, and was much hotter than the inside of the hottest stars are now; but this is highly speculative, though highly interesting.

Another and more practical riddle is: What have huge stars like Y Cygni been doing throughout the 2000 million years or so since the universe fairly started to expand? Such a star is spending its store of energy at least five hundred times faster, in proportion to the total supply, than is the Sun. The transformation of the whole mass from hydrogen to helium would keep it going, at its present rate, for only about 200 million years. Whether this means that these massive stars have begun to shine rather late in the history of the Galaxy, or that, after all, they have still greater stores of energy to draw on, in ways as yet unknown, must be left to the future to determine. But it is reasonable to suppose that, if still more massive stars, which would be far brighter than any now known, had once existed, they would have burned themselves out by this time—so that the question with which we started can be at least tentatively answered.

PLATE XII

(Photographs by Charles Ross, Dresden News)

THE DRESDEN METEORITE

A—Mr. Solomon excavating the meteorite.
B—The meteorite immediately after recovery.
C and D—The main mass before and after washing.

## METEOR NEWS

**Observations relating to meteors and meteorites are cordially invited.**

### THE DRESDEN METEORITE

By W. G. Colgrove

(with Plate XII)

ON the evening of July 11 at 8.45 a few of us were standing on the upper campus of the University of Western Ontario at London watching the first stars appear when suddenly a great flare from the north-east lighted up the lawns and trees all around us. It was the passing of an unusually bright meteor which immediately exploded high in the air and somewhat behind us and then, shooting a little to the north overhead, whizzed toward the south-west leaving a trail of bluish-green light about 5 degrees wide and extending from north of Vega to near Spica. No sooner had it reached a point apparently half way across the campus than it burst again and was followed by a similar band of orange-red light of equal dimensions. Finally it burst a third time and disappeared over the tree-tops on a distant hill. During its entire course the meteor itself shone as an intensely brilliant object apparently about the size of a baseball six feet away and surrounded by a spherical yellowish glow as large as a football and shot through with short streamers of different colours. At each explosion a large puff of ashy smoke about ten degrees across arose and remained for nearly an hour in the air. The main feature lasted only about four seconds, but it was the grandest moving sky-picture I have seen since the great comet of 1882.

As soon as word came that it had fallen near Dresden and had been sold for $4.00, Dr. H. R. Kingston, Head of the Department of Mathematics and Astronomy, authorized a committee of investigation composed of Dr. E. G. Pleva, professor of geography, and the writer to make a tour of examination for the collection of evidence. The next day we arrived in Dresden where we found the meteorite in the printing office of Mr. Ross, surrounded by a questioning crowd,

a resistance of 100,000 ohms between points on the fractured surface. There was no reaction between points on the fused surface. A small black, threadlike veinlet was noted in the fragment. This was due, in all likelihood, to the fracturing of the stone prior to its entrance into our atmosphere. The vein filling is of nearly coal black colour. From the "crust" and the gray colour of the interior, the "meteorite" from which the fragment was derived would be classed as belonging to the *stony* type. However, the strong magnetic properties, the apparent great weight, and the conspicuous crystal points indicated a stony meteorite high in nickel and iron. It is likely that a complete analysis would place the meteorite in the intermediate group, the stony iron or siderolite group.

2. *"The Meteorite"*: We found the "meteorite" had been placed in the custody of Mr. Charles Ross, editor of the Dresden News, who was exhibiting it in the window of the newspaper office.

a. *Description of the Meteorite*: The stone weighs eighty-eight pounds and approximates the dimensions of a field watermelon 14 inches long and 9 inches in diameter. The surface is crusted with the characteristic black imperfect glass coating of the stony meteorites. Some fragments were lost in the recovery of the stone and others were chipped off by "interested" parties. About 60% of the surface crusting remains, and about 95% of the meteorite by weight is still in the one piece despite the attacks by souvenir hunters.

When the meteorite was placed on exhibition on Wednesday, July 12, the fractured surfaces were bright gray, but 24 hours later the surfaces had a distinct oxidized or "rusty" appearance. This may be due to the presence of native iron, *oldhamite* (sulphide of calcium) and *schreibersite* (phosphide of iron and nickel). These minerals are unknown (or at least rare as in the case of native iron) in the earth's crust since they do not exist long in the presence of oxygen and moisture. This may account for the apparently rapid weathering.

b. *Description of the Fall Site*: The meteor fell in a beet field on the farm of Dan Solomon, a few miles out of Dresden. Mrs. Solomon saw the meteor fall into the field. Mr. Solomon dug the stone out the next morning and sold it for $4.00. The news story is essentially correct.

The fall of the meteorite was accompanied by noises variously described as resembling fire of guns and thunder.

It was impossible to find any evidence of the so-called white ash formed by the passage of "stone" through the clay. According to reports, the meteorite was found at a depth of seven feet.

While this depth seems quite extreme for an 88-pound stone, the evidence for depths is extremely contradictory. The absence of more "splatter" over a great area was surprising, but all evidence of "splatter" may have been obliterated by the feet of sightseers and a morning shower. Also surprising was the fact that the clay did not seem more compacted at the bottom of the hole. However, the hole had filled with ground water and the clay may have softened sufficiently to permit the prodding of the crow bar.

c. *The Owner*: Dr. Luke Smith, the owner of the meteorite, took the stone from Dresden to his home in Chatham, July 13.

University of Western Ontario.
July 13, 1939.

## RESULTS OF THE STUDY OF 66 ORBITS OF METEORITES

(A preliminary note)

By I. S. Astapowitsch

In 1938 I completed at the Astronomical Institute of the Moscow University the investigation of orbits of 66 meteorites out of a total of 584, fallen up to January 1, 1938 (according to P. M. Millman's statistics) and kept in the museums of the world. Orbits of the following meteorites have been obtained:

(1) Novgorod Velikij (lost), (2) Novaya Erga (lost), (3) Hradschina, (4) Barbotan, (5) L'Aigle, (6) Weston, (7) Stannern, (8) Toulouse, (9) Erxleben, (10) Agen, (11) Wessely, (12) Blansko, (13) Little Piney, (14) Cereseto, (15) Braunau, (16) Gütersloh, (17) Mezö-Madarasz, (18) Quenggouk, (19) New Concord, (20) Iowa City, (21) Pillistfer, (22) Orgueil, (23) Knyahinya, (24) Pultusk, (25) Motta di Conti, (26) Slavetic, (27)

Hessle, (28) Krähenberg, (29) Lancé, (30) Orvinio, (31) Khairpur, (32) Homestead, (33) Stalldalen, (34) Rochester, (35) Tieschitz, (36) Mócs, (37) Tysnes, (38) Ochansk, (39) Jelica, (40) Forest City, (41) Björbole, (42) Leonovka, (43) Tomakovka, (44) Podkamennaya Tunguska, (45) St.-Michel, (46) Holbrook, (47) Appley Bridge, (48) Treysa, (49) Boguslavka, (50) Kaschin, (51) Saratov, (52) Simmern, (53) Nately (lost), (54) Padvarninkaj, (55) Chmelevka, (56) Paragould, (57) Staroje Boriskino, (58) Karoonda, (59) Archie, (60) Prambakirchen, (61) Wilkomir, (62) Pasamonte, (63) Athens, (64) Sioux County, (65) Pervomajskij, (66) Crescent.

Five of them are iron meteorites (Nos. 3, 23, 48, 49, 53). Nos. 7, 54, 57, 62, 64 and also Jonzac and Juvinas are eukrites, 2 are carbonaceous meteorites (Nos. 22 and 29), No. 44 is unknown. Forty-nine orbits proved to be either coinciding *inter se*, or with orbits of great showers of slow meteors and fireballs, elliptic as well as hyperbolic. Of the latter except for 2 previously known (cosmical showers of Scorpiids and Taurids), a series of cosmic showers were found (Virginids, Cancrids, Eridanids, Cygni-Lacertids, etc.); several meteorites also belong to them. Six of the elliptical orbits of meteorites coincided with certainty with the orbits of the comets 1092, 1702, 1797, 1851 I, 1874 II and 1790 III, the meteor radiants being well known for all of these, except 1702. To the Carolina Herschel Comet 1790 III belong the meteorites Nos. 5, 14, 16, 17, 26, 33, 38 and 40, besides the family of comets connected with it and the four meteor showers (CCXLVII, CCXLVIII, CCXXXII, CCXXXVI, according to Denning). They proved to be of the same composition (all of them brecciated chondrites). The orbits of all these bodies (3 comets, 4 showers and 8 meteorites) pass near the same point in space, situated in the direction $\lambda = 216°$, $\beta = +3°$ at a distance of 1 astronomical unit from the sun. All cometary meteorites proved to be stone meteorites, chondrites of bronzite and hypersthene, i.e., of the composition $(Mg, Fe)_2\ Si_2\ O_6$, whence I predicted the probable presence in the spectra of cometary meteorites in the first place of emission lines of iron, magnesium and silicon, and in the spectra of the comet nuclei near the sun of Fe, Mg, and O. In November, 1938, Dr. S. V. Orlov, Professor of the Moscow University, informed me that he identified on the basis of visual observations the lines of Fe, Mg, and O in the spectra of comets which approached the sun closely; as is known from Dr. P. M. Millman's works, Fe

was found in the spectra of the Leonid and Perseid meteors. T. V. Vodopianova, on her side, extended the family of the comet 1790 III to several new comets with orbits crossing the above mentioned point. Nine orbits of meteorites are without doubt elliptic, 31 are hyperbolic, the rest (26) come close to parabolic or are uncertain. Seven eukrites proved to have come from quite different directions, some of them have been subjected to a second metamorphose or re-heating outside the solar system. All 5 iron meteorites also penetrated the solar system along hyperbolae, having nothing in common (both hexahedrites and octahedrites). Two carbonaceous meteorites (Nos. 22 and 29) are also foreign to the solar system. To the gigantic cosmical shower of Scorpiids (fireballs, meteors and telescopic meteors) belong 5 meteorites (Nos. 4, 11, 12, 24 and 42), all of them being identical (grey veined chondrites); they fell from the year 1790 to 1900, and in the case of appurtenance to the shower Nos. 1 and 7—in the course of 5 centuries (from 1421 to 1933). On the whole, the meteorites of the solar system display a curious uniformity. Their brightness coefficients (albedo) on fracture have the values 0.2-0.3 and approach those of the asteroids, the cosmical material being much more heterogeneous. This gives independent confirmation for the difference of physical properties, and also of heights and spectra between "solar" and "stellar" meteors. To account for the origin of the meteorites we must admit the presence of several sources, whether once in existence or still existing in a number of different regions of the galaxy. The catastrophically fast cooling characteristic for many meteorites may be connected with the ejection into cosmic space of differentiated fused masses probably at the times of great cataclysms with such bodies as for instance the dark companions of stars. The formation of new comets in the solar system, continuing also in our day, is caused by the effect of the destruction of a small section of the surface of one of the small bodies of the solar system (of the numerous but as yet undiscovered small asteroids—or, what is the same—of large meteorites of the Hermes 1937 VB type), in its collision with a "typical" small meteorite. The emission of the gases ($CH_4$, $N_2$, CO, $CO_2$, etc.) contained in each meteorite, and in normal condition exceeding in volume the volume of the meteorite containing them, is evidently akin to the production

of cometary gases. On the whole, the ordinary so-called comets are products of insignificant disintegrations caused from time to time by collisions of meteorites and asteroids, the eccentric orbits of the latter not suffering any conspicuous changes. Jeans' theory of dissipation applied to comets is not inconsistent with the figures denoting the age of ordinary comets (hundreds of years) which gradually return to their pre-collision meteorite state. The number of these asteroids as well as the number of meteorites contained simultaneously in the solar system is much higher than was hitherto supposed.

In general, there also exist some other sources of meteorites in various parts of our galaxy.

Moscow University.
July 9th, 1939.

## Note on the Dresden Meteorite

The recorded Canadian meteorite falls have been few in number (i.e., De Cewsville 1887, Beaver Creek 1893, and Shelburne 1904), so that the fall of the Dresden Meteorite is of particular interest. The scientific value of the occurrence is further enhanced by the fact that it took place early on a summer evening when a large number of people were outdoors and witnessed the phenomenon. Because of this fact the knowledge of the air-path should be fairly complete. Rev. W. G. Colgrove, the enthusiastic president of the London Centre of our Society, and Professor Pleva of the department of geography at the University of Western Ontario, have described above the chief details of the fall. The writer recently spent the greater part of a week travelling through southern Ontario in the neighbourhood of London and Dresden for the purpose of interviewing eye-witnesses and collecting as much scientific information as possible about the fall and, in collaboration with Professor Reavely of the Department of Geology at the University of Western Ontario, publication of a detailed scientific account has been planned for a future issue of the Journal. The writer would like to have all eye-witness accounts of the great fireball of July 11, no matter how lacking in detail they may be. All notes concerning sounds heard are of particular interest.

It is also very important to have a record of all authentic pieces of the meteorite which have been found. It is sincerely hoped that members of the Society will do what they can to insure a complete scientific record of this interesting event.

### Preliminary Report on the Perseid Campaign

On the whole the weather for the five nights scheduled for Perseid observation was above the average. The most unfortunate occurrence from the standpoint of the meteor observer was a remarkably brilliant auroral display on the night of Aug. 11-12. This display covered most of the sky from dusk till dawn and made both visual and photographic observations of meteors very difficult. In spite of this fact, however, a preliminary survey indicates that the Perseid programme was highly successful. All stations have not yet reported but it is known that one spectrum and 12 direct photographs were secured at the Dunlap Observatory, all these being taken with the rotating shutter, and that well over 20 direct photographs were secured at co-operating stations. At least 9 meteors were photographed at two or more stations. These results are all the more gratifying since the shower was not marked by the appearance of any meteors of great brightness or long enduring trains. The success of the programme is in large measure due to the number of interested amateurs who assisted with the photography, and clearly demonstrates the value of amateur co-operation in this field. Approximately 2,500 visual observations have been received from 21 stations. A complete account of the programme will appear in a future issue of the Journal. P. M. M.

# NOTES AND QUERIES

**Communications are invited, especially from amateurs. The Editor will try to secure answers to queries.**

## Death of Father Luis Rodés

It was with great regret that the present writer learned of the death of Rev. Fr. Luis Rodés, S.J., on June 7 last.

The construction of the Observatory of the Ebro was begun in 1904 by Rev. R. Cirera, S.J., who became its first director. From its inception observations on the sun and moon and on meteorological conditions have been carried out with exceptional regularity and persistence. In 1919 Father Rodés succeeded as director and he discharged his duties with peculiar devotion and success. He maintained the periodic publications of the observatory and in addition he prepared some valuable discussions of the very numerous observations which had accumulated. He also issued an excellent atlas of clouds from photographs taken at the observatory, and a splendid volume (in Spanish) entitled "El Firmamento."

Father Rodés travelled extensively. On several occasions he visited America and he spent some time in study at the Harvard Observatory. He also found his way to Toronto. He was an active scientist and an amiable gentleman. In August 1938 he attended the meeting of the International Astronomical Union in Stockholm, and although he was far from being well he retained his joyous nature and kindly manner. A little incident remains in the writer's memory. On the evening of the first day of the meeting the delegates and their friends were entertained by the city of Stockholm in their magnificent Town Hall. The visitors inspected its numerous halls and rooms, and while passing through the council chamber, furnished in red, the writer sat for a few seconds in the fine leather-covered chair of the presiding officer. Father Rodés, a few yards away, cheerfully called out: "You would make a good mayor, Professor Chant."

A circular letter from Rev. Fr. Antonio Romana, the new director, which is printed herewith, will be read with interest.

*Observatorio del Ebro—Dirección*

Dear Sir,—I have the painful duty of giving notice to our dear friends and colleagues of the death of the Rev. Fr. Luis Rodés, S.J., who for nearly twenty

years had been the Chief Director of this Observatory. He passed away on the 7th instant at 57 years of age in the town of Bianaraix (Mallorca, Balearic Islands).

The excellent work achieved by Fr. Rodés, not only in his daily labour as the head of the Observatory, but contributing efficaciously to so many International Congresses and taking an active part in both national and foreign scientific Corporations is well known to all; the high esteem that he enjoyed, is well proved by the great number of Institutions of all countries, who had offered a seat of honour amongst its members.

For several years back he was suffering from arterial hypertension which latterly became worse on account of the moral suffering due to the difficult circumstances in which he had to discharge his activities. But above all the destruction by the reds, on the 12th April 1938, seven days before the fall of Roquestas into the hands of the nationalists, of the work of his whole life, depressed him so that he repeatedly entreated his Superiors the favour of being relieved of the post he was holding.

This was granted to him lately and when all seemed to indicate that after a long repose he could once more resume his scientific researches, a blood vessel broke, putting an end to his existence. Surely the Creator, whose wonders had been so highly praised and described by Fr. Rodés in his master work EL FIRMAMENTO, has called him to partake of His Glory, opening to him for ever the treasures of His Infinite Wisdom.

I take advantage of my giving you account of the irreparable loss of our beloved Fr. Rodés and of begging you a pious remembrance of such a worthy man of science as he was, to offer you my services as the new Chief Director, hoping you will continue giving in the future to this *Observatorio del Ebro* the same assistance and consideration you have given to same in the past.

Yours sincerely,

ANTONIO ROMANA, S.J., D.Sc.

Tortosa (Roquetas)
June 1939

## ASTRONOMY IN FICTION

A trusty friend, whose initials "F. T. S." have on several occasions been seen in this column, writes that during the summer he turned to reading fiction as an antidote to the sombre facts of a world drifting into chaos. Among the books he read were: "Seasoned Timber" by Dorothy Canfield, "Iron and Smoke" by Sheila Kaye Smith, and an old book, "With Kitchener to Khartum," by the noted war correspondent, G. W. Steevens.

His letter continues:

Perhaps we should not look for fact in fiction, but one author had Orion high in the sky in the month of June, and a little later a young moon was sinking

behind eastern range of mountains. Another book told of an evening dinner where "they drank a light Barsac, delicate and dry." Then through the window "they saw the yellow crescent of the moon moving upward . . . memory would always hold the picture of darkness and candle light, of a woman's beauty mirrored golden brown in the pool of a polished table, of a crescent moon climbing the sky." (It must have been very beautiful, or the Barsac stronger than suspected.)

A war correspondent ought to know better than write the following, but one must admire the forthright directness of his statements, which are soldier-like and admit of no contradiction:

"The young moon was climbing up the sky when we set off into the desert. At half past one I saw the moon stooping down to meet the fringe of palm trees."

One evening during the summer I was told by the radio announcer for a much-advertised gasoline that it was the date of a new moon, and that I should get out the car and take a look at the beautiful spectacle. The calendar verified the new moon, but I decided to wait a couple of days until the moon had drawn away from the sun sufficiently to form at least a crescent.

C.A.C.

### The Colgrove Planet Placer

Recently we have received a copy of a "planet placer" designed and published by our very active member, Rev. W. G. Colgrove, of London, Ontario. The base of the apparatus is made of cardboard, about eight inches square. On its face are drawn representations of the planetary orbits. Nine cardboard arms, attached at the centre, carry the planetary discs around these orbits. A dial attached at the earth's centre carries a circle divided into 24 hours R.A., and into the twelve zodiacal signs. In actual use, the right ascensions of the planets are read from our Observer's Handbook, and the various arms then adjusted to lie in the given directions. The whole plate may then be rotated so as to correspond to the hour chosen, and the positions of the planets will be represented. Due to the necessarily small diameter of the right ascension dial, the setting is not highly accurate, but the Planet Placer does give a very good representation of the directions of the planets at any time. The distance scale is, of course, distorted. Mr. Colgrove is to be congratulated on the neatness and suitability of this apparatus, which undoubtedly will prove of great convenience to many observers. Copies are obtainable directly from Mr. Colgrove, 2 Christie St., London, Ontario, at a price of 30 cents each.

F. S. H.

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